7. OPTICAL PHENOMENA OF THE ARCTIC

One of the unique aspects of an assignment in the Arctic is the ample opportunity to view a host of optical phenomena that occur there. Many of these phenomena arise from the suspension of ice crystals in the polar atmosphere; however, the presence of strong surface inversions is also responsible for refraction of light rays. The combination of these two features of the Arctic atmosphere make for a variety of optical effects.

7.1 Refraction

Sunlight is composed of a mixture of colors ranging from violet to red, not to mention the invisible ultraviolet and IR radiation on the edges of the solar spectrum. A prism, as shown in Fig. 7-1, causes the rays of different colors to be deflected and separated as a result of *refraction*. Refraction comes about because the speed of light depends on the property of the medium through which the light passes. Consider the passage of light from one medium, water, into another medium, air (Fig. 7-2). The wave speed is greater in air than in water, and as a result, when a wave front emerges from the water, it is reoriented because the part of the wave in the air moves faster than the part in water. The bending of light rays is easily demonstrated by observing a pencil partly immersed in water, as in Fig. 7-3. When viewed from the side, the pencil appears shorter than it actually is because the light rays coming from all parts of the pencil under water are deflected at the surface of the water.
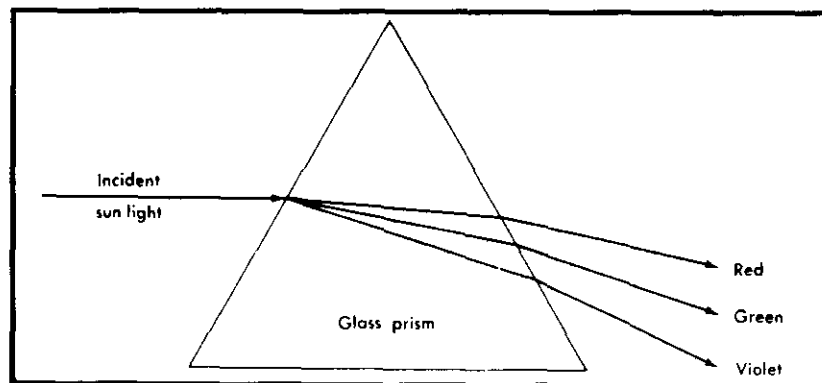

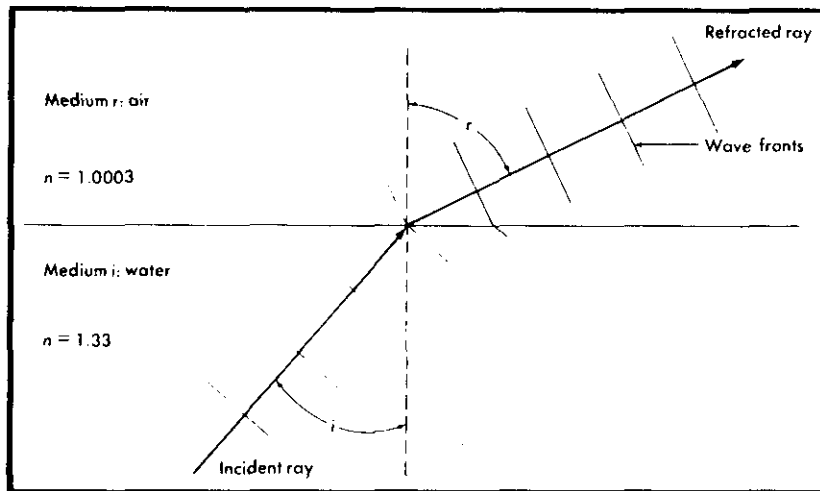*Figure 7-1.   Sunlight Passing Through a Prism (Battan, 1984).*

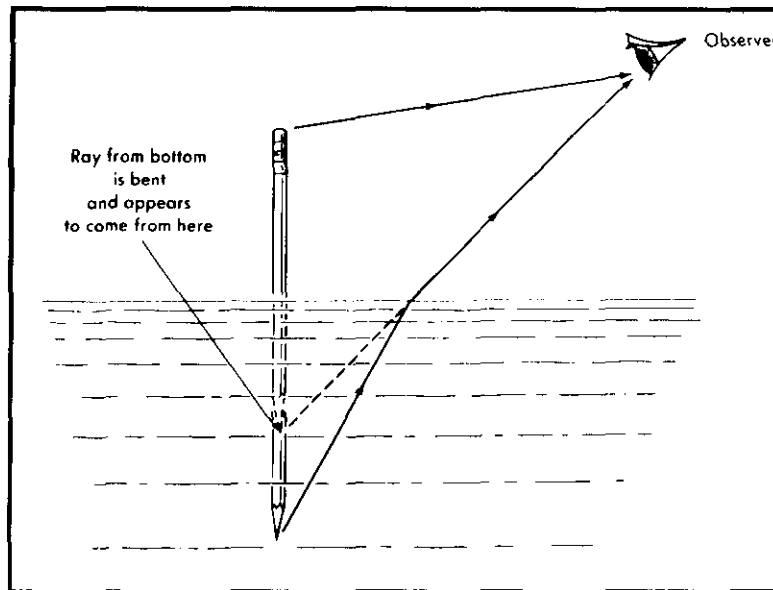*Figure 7-2. An Example of Refraction (Battan, 1984).*

Figure 7-3. Rays Bending from One Medium to Another (Battan, 1984).

The velocity of light in any medium is given by the speed of light in a vacuum (3 × 10^8 m/s) divided by a quantity called the *index of refraction*. Table 7-1 shows the indices of various substances and the corresponding speeds of light through them. For example, light passes through water at a velocity of 2.26 × 10^8 m/s, a value substantially less than the speed of light in air. The degree of refraction as a light ray moves from one medium to the next depends on the difference in indices of refraction of the two media.

The change of direction of a light ray is given by *Snell's law of refraction*. The law states that the greater the ratio of the indices of refraction, the greater the bending of the ray as it moves from one medium to the next.

TABLE 7-1. INDICES OF REFRACTION (N) OF VARIOUS SUBSTANCES FOR VISIBLE LIGHT* (BATTAN, 1984)

Medium	n	Speed of light** ($\times$ 10^8 m/s)
Vacuum	1.0000	3.000
Air (lower atmosphere)	1.003	2.999
Ice	1.31	2.29
Water	1.33	2.26
Olive Oil	1.47	2.04
Flint Glass	1.61	1.86
Diamond	2.42	1.24

* The values in this table apply specifically to a wavelength of 0.589 μm (yellow), but they are approximately correct for all visible radiation.

** Speed $v = c/n$, where $c = 3.000 \times 10^8$ m/s.

The value of the refractive index depends not only on the properties of the medium but also on the wavelength of the electromagnetic radiation. Over the visible part of the spectrum, the range of the refractive index is small. Nevertheless, the small differences are important because they lead to the dispersion of white light into various color components as the light passes through a glass prism, raindrop, or an ice crystal. Since the refractive indices at the violet end of the spectrum are larger than those at the red end, the violets and blues are refracted more than the yellows and reds, in accordance with Snell's law.

7.2 Rainbows

When the Sun illuminates sheets of water droplets, colorful arcs appear around the antisolar point, i.e., the point 180 degrees away from the Sun along a great circle. These arcs are called *rainbows*, although they may be caused by dew droplets on the ground, or by sprays from waterfalls, fountains, or garden hoses.

The *primary rainbow* has a red outer border whose angular radius is roughly 42 degrees. The *secondary rainbow* is generally a broader and less bright band with red on the inner border and a radius about 50 degrees. The area between these two rainbows appears darker than the rest of the sky. The *supernumerary bows* that appear inside the primary and outside the secondary rainbows are an integral part of these rainbows; they show fewer and less distinct colors and are frequently so faint as to be visible only to an experienced observer. Figure 7-4 shows schematically the geometric optics of primary and secondary rainbows. Considering the primary rainbow, a sunray entering a water droplet is refracted, once reflected, and again refracted on leaving the droplet. Since the various color components of sunlight are differently refracted, the component rays diverge. Thus, only one ray emerging from a droplet may reach a given observer. Moreover, each eye of the observer receives light from a different droplet for each color from every point of the rainbow.

The secondary rainbow is produced in a similar manner, but the light ray is twice internally reflected before being refracted out of the drop. For this reason, the color sequence is reversed, and because of the greater divergence of the emerging color components, the secondary rainbow is broader. It is also only about one-twelfth as bright as the primary bow because of the light lost in the multiple optical processes involved.
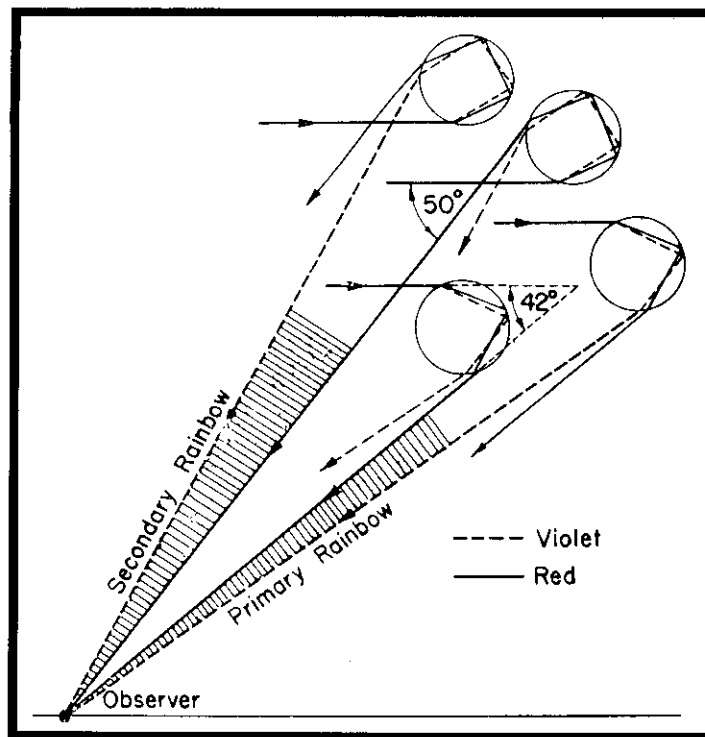

Figure 7-4. Schematic Diagram of Geometric Optics of Rainbows (Neuberger, 1966).

7-4

Figure 7-5 shows that a rainbow always appears in the opposite side of the sky from the Sun. By standing in front of the Sun while viewing a distant shower, the observer will be able to see a rainbow. Because of the geometry involved, when rainbows are observed from the ground, they appear as semicircles. Thus, flying over a region of raindrops when the Sun is high in the sky, the observer will have the experience of looking down and seeing a rainbow in the form of a complete circle or ring.
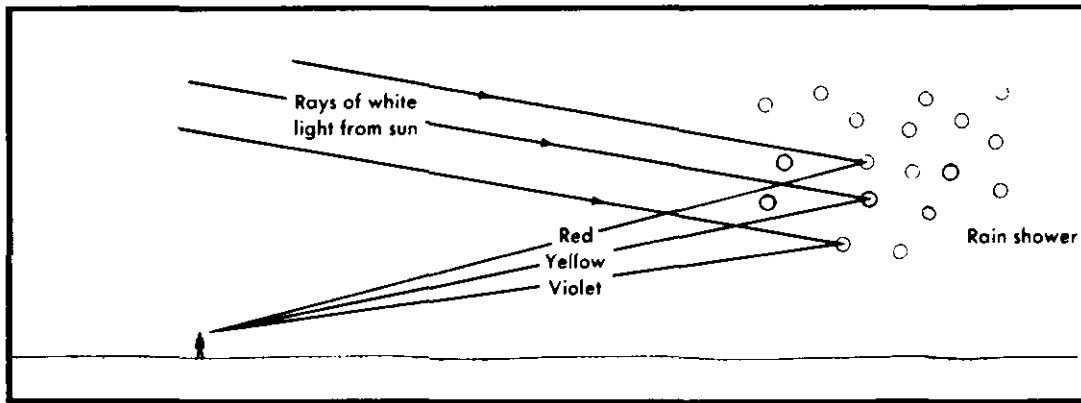

Figure 7-5.   The Primary Rainbow (Battan, 1984).

7.3   Halos

Ice crystal clouds can produce a large variety of luminous arcs and circles that are called *halos*. The most common one is a bright ring surrounding the Sun or the Moon and having a colored or whitish appearance. The halo occurs because of the refraction of light as it passes through ice crystals in the shape of hexagonal prisms (Fig. 7-6). When a thin, uniform cirrostratus deck containing such crystals covers the sky, the halo may be in the form of a complete circle having an angular radius of 22 degrees (the angle between lines from the eye to the Sun and to a point on the halo).
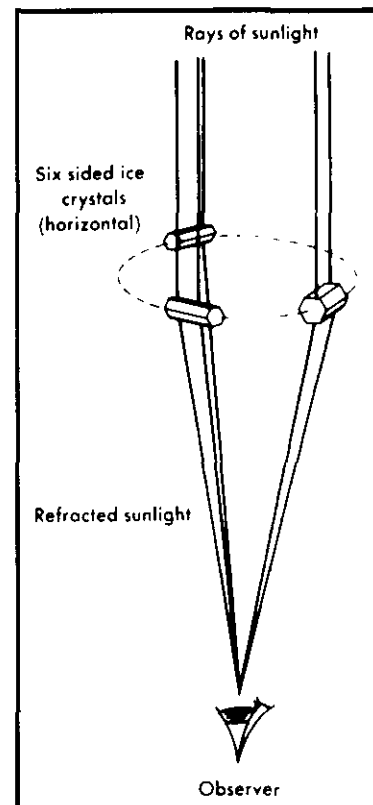

Figure 7-6.   Formation of a 22-Degree Halo (Battan, 1984).

More often a cloud of ice crystals covers only part of the sky, and as a result, only a segment of a halo is seen. A hexagonal ice prism in the process of refraction separates white light into its component colors. Since blue waves are bent more than red ones, the inside of the halo is red, the outside blue. Most often the colors are subtle, and thus halos appear mostly white.

Figure 7-7 shows the ray path through a hexagonal platelet or column by which the halo of 22 degrees is produced. In order for a complete ring around the Sun to be visible, the ice crystals must be randomly oriented. This condition also holds true for the halo of 46 degrees that is produced by a refracting angle of 90 degrees; that is, a ray enters the side of a hexagonal prism and leaves the base of the crystal as shown in Fig. 7-8, or the ray enters the base and leaves the side. The 46-degree halo is rarely seen as a complete circle, but exhibits more distinct colors than does the halo of 22 degrees.

Of the great variety of halo forms, only the most common halos are shown in Fig. 7-9, in which the Sun is represented by a small circle in the center. The various features are depicted for the Sun's elevation of about 25 degrees. Thus, the lower portions of this diagram are below the horizon for an observer on the ground.
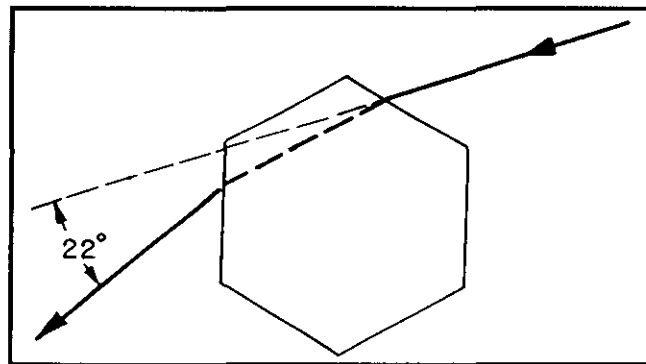

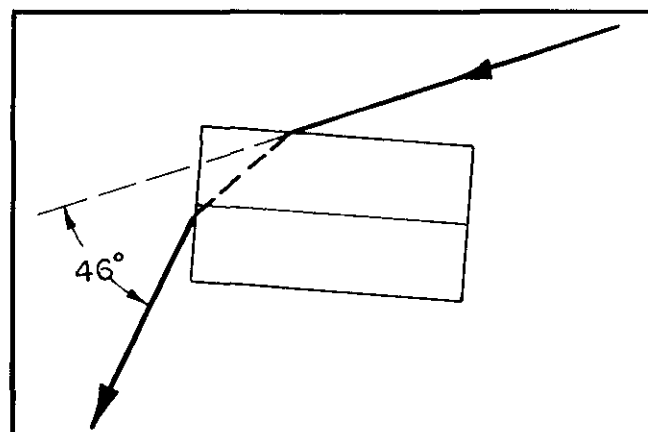*Figure 7-7. Ray Path Through a Hexagonal Crystal (Neuberger, 1966).*

Figure 7-8. Ray Path for a 46-Degree Halo (Neuberger, 1966).

7-6

Occasionally a species of halo can be seen consisting of a faint, white circle passing through the Sun and running parallel to the horizon. This unusual effect is called a *parhelic circle*. It is caused by simple reflection from the faces of ice crystals (in the form of hexagonal prisms) having their long axes in a nearly horizontal plane as though they were tiny mirrors.

When ice crystals in the form of hexagonal prisms fall with long axes vertical, refraction causes the formation of luminous spots on both sides of the Sun at an angular distance of 22 degrees. Either of these spots is a *parhelion*, but the more popular name is *sun dog*. Figure 7-10 shows a 22-degree halo with sun dogs embedded to the left and right of the horizon.
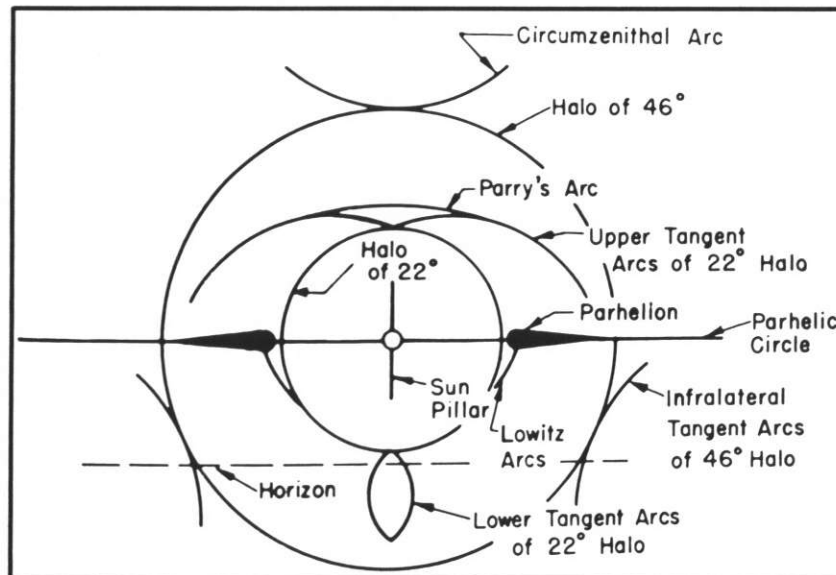

Figure 7-9.   Common Observable Halo Phenomena (Neuberger, 1966).

Figure 7-10.   Halo with Sun Dogs and Sun Pillar (Battan, 1984).

Occasionally shafts of light extend vertically either directly above or below the Sun. Commonly known as *sun pillars,* they are most frequently seen near sunrise or sunset (Fig. 7-10).

7.4 Coronas and Related Phenomena

Sometimes the Sun or Moon is partially obscured by a thin cloud and is surrounded by a ring of light called a *corona,* a word meaning "crown." At times, a corona may be in the form of a luminous disk having the Sun or Moon at its center. Coronas subtend angles of only a few degrees and therefore are much smaller than the common 22-degree halo. When a corona exhibits coloration, it is blue on the inside and red on the outside, opposite to the order of colors in a halo. Coronas are produced by clouds of water droplets as a result of an effect called *diffraction.* In diffraction, a light wave spreads behind an obstacle into the region that might normally be expected to be in shadow. Light waves coming from the Sun or the Moon toward an observer are slightly deflected around cloud droplets. When the waves interfere with one another on the observer's side of the droplets, concentrations of light occur in circles around the Sun or the Moon. Thus, whenever a corona is visible, the conclusion can be drawn that the cloud partly obscuring the Sun or Moon is made up of water droplets. In general, the smaller the cloud droplets, the larger the radius of the corona. Figure 7-11 shows a corona.

Occasionally, thin clouds high in the sky exhibit patches of color of the purest blue, green, and red. They may appear either when the Sun is low or high. Such clouds, called *iridescent clouds,* usually are observed to be within 30 degrees of the Sun and also are thought to be caused by diffraction. Recall that the Sun's rays are deflected around patches of uniform water droplets, and the light waves interfere with one another in such a fashion as to separate the various color components.

Figure 7-11. An Example of a Solar Corona (Battan, 1984).

The coronal phenomena around the light source have their counterparts around the point opposite the light source, such as around the antisolar or antilunar points. For example, an observer in the mountains seeing his slightly enlarged shadow on a fog bank or cloud beneath (the *brockenspecter*), often sees the shadow of his head encircled by brightly colored rings, the *anticorona or glory*. The anticorona can often be observed from a plane when looking on the shadow cast by the plane on the clouds below it.

7.5 Mirages

Four different types of mirages occur: the inferior image, which projects an image below the source; the superior image, which projects the image above the source; the towering image, which makes something appear taller than it really is; and the stooping image, which makes an object appear shorter.

7.5.1 The Inferior Mirage

An excellent example of the *inferior* mirage is the shimmering lake that appears on freeways or at the base of mountains. In hot, dry regions, air layers near the surface of the Earth are hotter, and therefore less dense, than those above it. When light strikes this superheated, low-density layer of air, it is refracted, or bent, so that it creates an optical illusion. For example, light from the sky may strike the hot air just above the pavement of a highway and be shot into a driver's line of vision. This situation is pictured in Fig. 7-12. The driver appears to see a pool of blue water in the road ahead but is actually seeing a mirrored image of the blue sky.
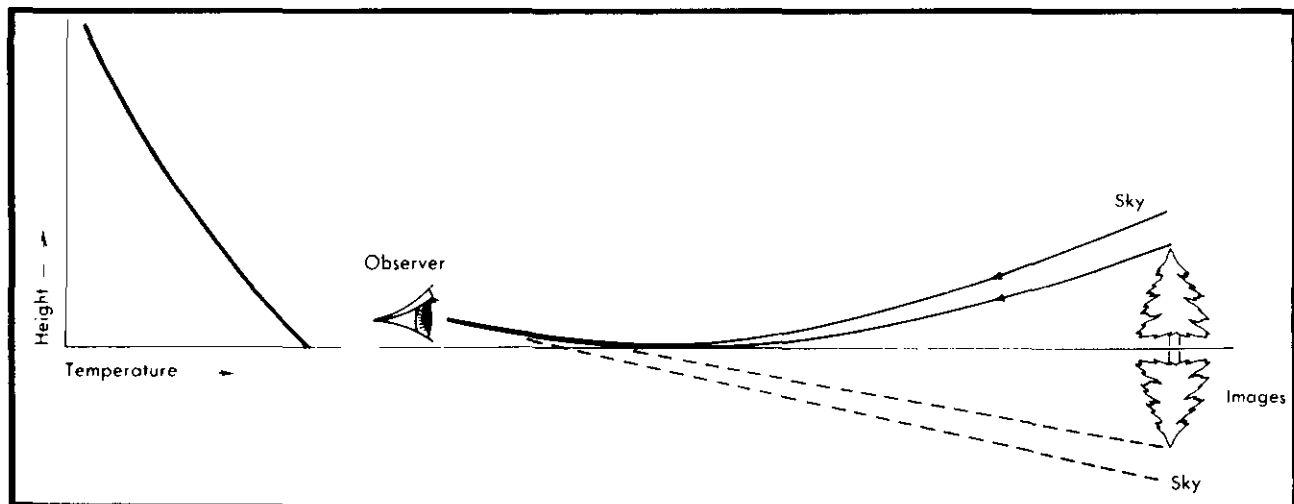

Figure 7-12. The Inferior Image (Battan, 1984).

If the light illuminates clouds or mountains before it is refracted, the driver also see mountains or clouds within the blue sky. Often, depending on the angle at which the light is bent, the images are inverted, making them look very much like reflections in a pool of water.

7.5.2 The Superior Mirage

The *superior* image works the opposite way from the inferior image. If an observer is standing in cool air with warm air above, light may be refracted back from space into the line of vision. Since some light will also travel directly from the source, the observer will see the actual object in the horizon and its inverted image floating in the sky. Figure 7-13 is a representation of the superior mirage effect.

One of the authors once saw in Antarctica a spectacular case of "looming." The location was at a coastal station where the early morning hours were characterized by a very strong surface inversion, on the order of 20 °F–30 °F (−7 °C to − 10 °C) in the lower 500 ft. On this particular morning a look seaward revealed what appeared to be hundreds of icebergs rather than the usual ten or twenty. Looming had allowed the observers to see far beyond the horizon to icebergs not normally seen. No doubt many erroneous estimates of distances by early explorers can be ascribed to this phenomenon.
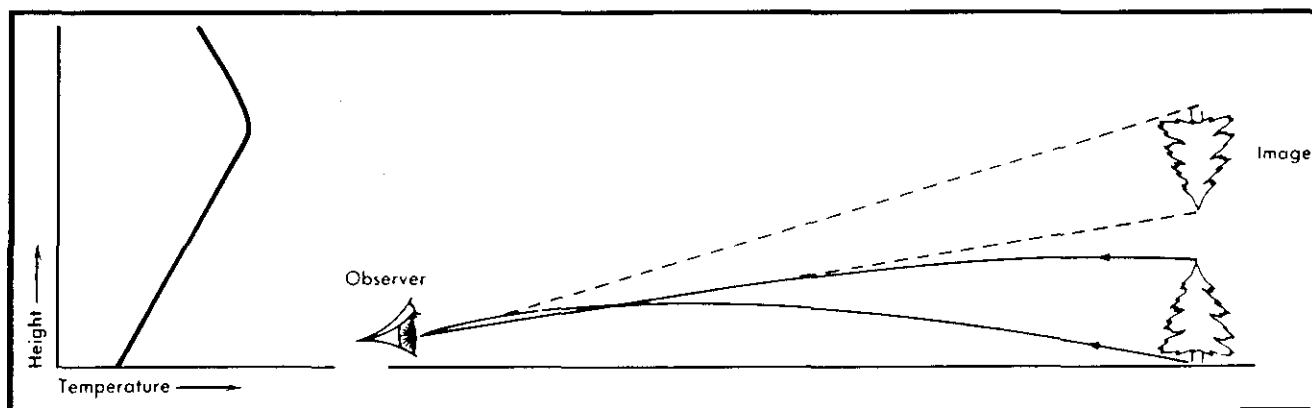

Figure 7-13. The Superior Image (Battan, 1984).

7.5.3 The Towering Image

Depending on the curvature of light rays, towering and stooping mirages also may occur. For example, the sails and mast of a ship may look elongated if seen from a distance. This *towering* mirage is caused by light moving through cool air and hitting warm air as it comes off the upper part (the sail) of the ship. The warm air bends the light back toward the observer. Since the light appears to the viewer to come from a higher source, the sail appears elongated. See Fig. 7-14 for an example of towering.

7.5.4 The Stooping Image

The *stooping* mirage, (Fig. 7-15) is an image that is contracted vertically. It works in basically the same manner as the towering image, but in this case the observer is standing in warm air, instead of cool air, thus forcing the light to level off into the observer's eyes and apparently reducing the vertical size of the object viewed.

Since stooping and inferior mirages occur in conditions where warm air is below cool air, these mirages happen most often on hot, dry land, where air nearest the Earth is usually the warmest in the atmosphere. Conversely, towering and superior mirages appear most often at sea, where air nearest the water is generally cooler than that above.
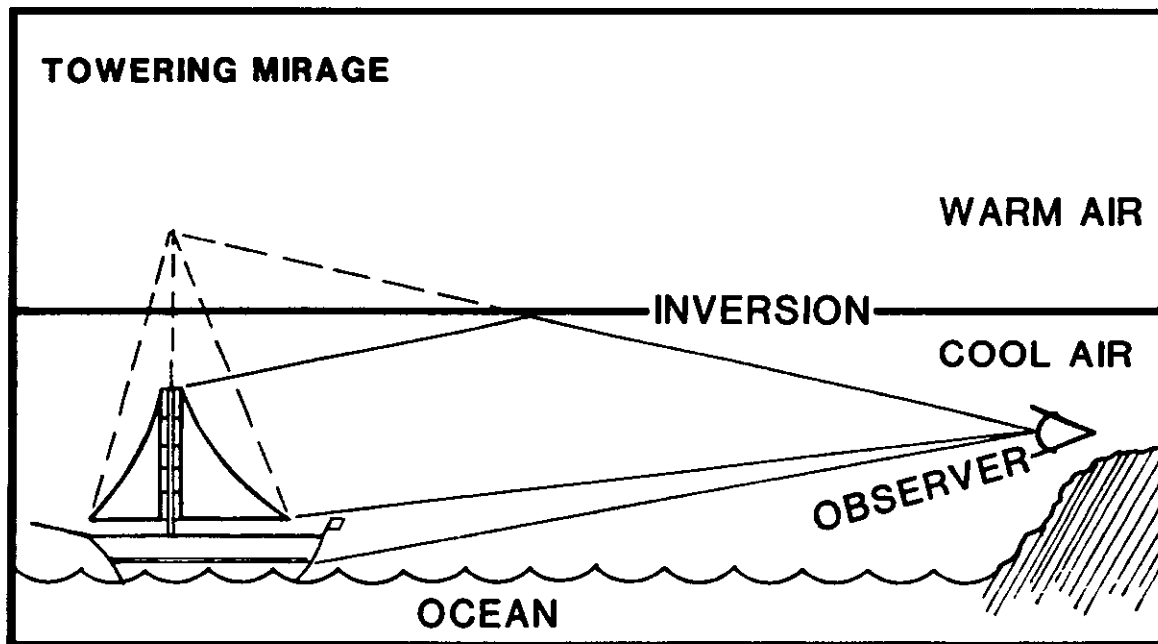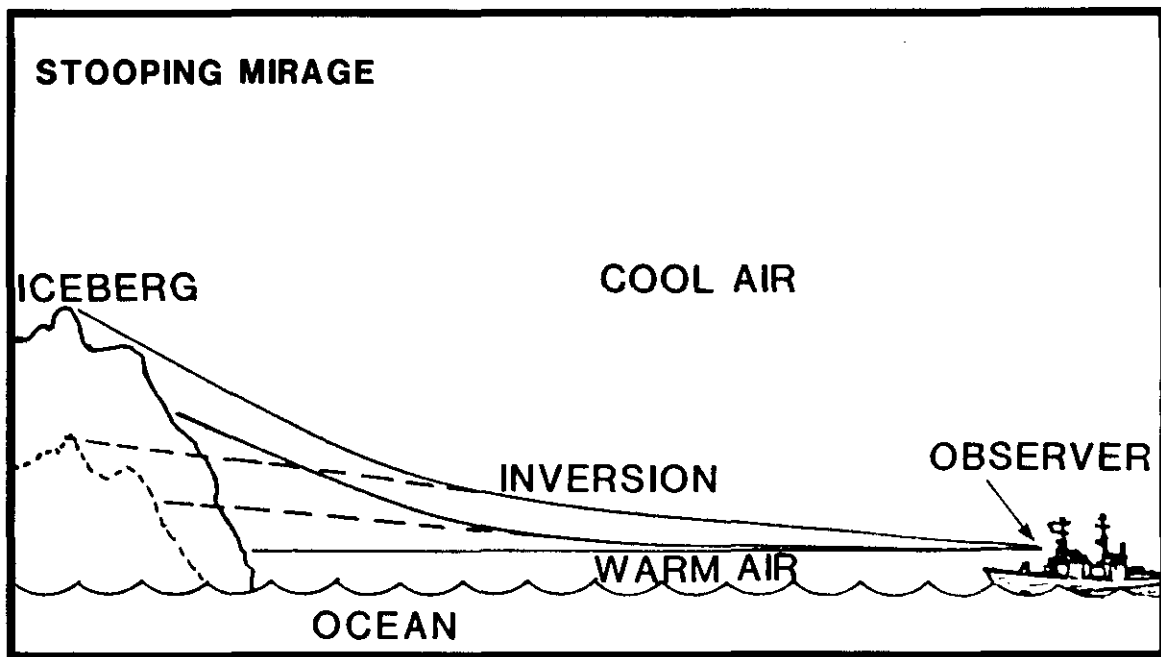

*Figure 7-14. The Towering Image.*

7-11

Figure 7-15. The Stooping Mirage.

7.6 Fata Morgana

Fata Morgana is the name given to a complex mirage in which distant objects become greatly elongated in the vertical direction and take on a bizarre aspect. A shoreline may be drawn out into tall cliffs and columns, and houses near the shore may assume the appearance of wondrous castles.

The phenomenon occurs under much the same meteorological conditions as the superior mirage and indeed often contains many of its features, though in more distorted form. The unusual stretching takes place in the layer where the normal upward lapse of temperature ceases and the elevated inversion begins. At the cold point in the sounding the density is at a relative maximum, and the degree of bending of the light rays changes sharply. The result is a vertical magnification of objects in the layer.

The fata morgana may be regarded as an intermediate stage between towering and the superior image, or a mixture of the two conditions. This mixture is evident in Fig. 7-16, where both the stretching and the tendency for formation of inverted images can be observed. Note that Fig. 7-16 is an etching produced from a drawing made in 1820. The subtleties shown in photographs of fata morgana do not reproduce well. Although the etching is overstated, it does provide the reader with the basic concept of fata morgana.
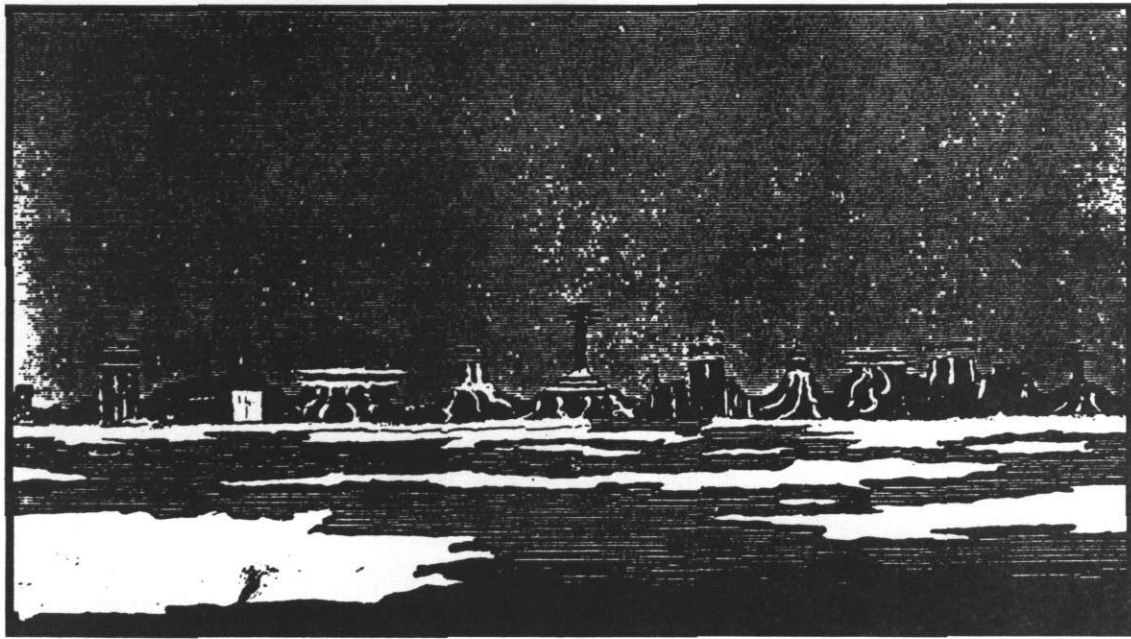
Figure 7-16.   An Example of Fata Morgana.

7.7 Iceblink and Water Sky

In summer a white or yellowish-white glare may be seen on the underside of clouds, as a result of the reflection of sunlight from snow or ice fields. When these reflections are intense, they are referred to as *iceblink*. Conversely, under the same circumstances dark patches or streaks may appear on the cloudbase above areas of open water. This condition is known as *water sky*. When other means of reconnaissance are not available, these phenomena are of assistance in navigating through the ice of the polar seas, since they give at least a rough idea of ice conditions at a distance.